Intensity Modulated Arc Therapy Principles and Perspectives

University of Maryland
Department of Radiation Oncology

Cedric Yu

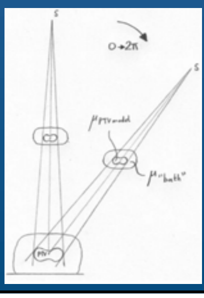
University of Maryland

Conflict Disclosure

- Advisory Council on Advanced Treatment Delivery, Varian Medical Systems, Inc.
- Patent License:
  - Varain: Single arc dose painting
  - Prowess & Varian: Direct Aperture Optimization
- Board of Directors, Prowess, Inc.

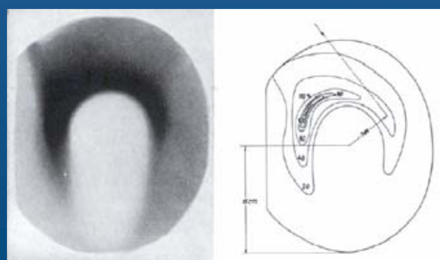
Rotational IMRT

Proimos BS. Synchronous protection and field shaping in rotational megavolt therapy. Radiology 1960;74:753–7.



Arc therapy

Wachsman F and Barth G. Moving field radiation therapy. University of Chicago Press. Chicago 1962 1-265.

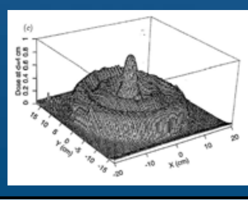


Dynamic Arc therapy

- Takahashi S. "Conformation Radiotherapy, rotation techniques as applied to radiography and radiotherapy of cancer". *Acta Radiol Suppl* 142, 1965
  - Introduces conformal therapy: MLC-shaped fields matches the beams-eye-view of target
  - Describes conformal arc therapy using MLC to outline the tumour through 360° rotation.

IMRT

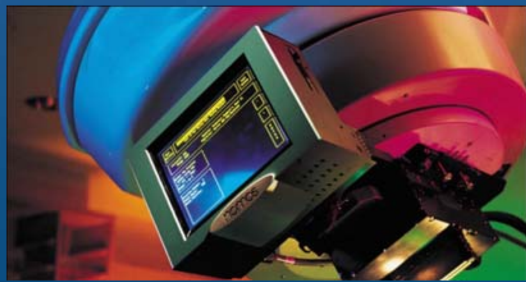
- A. Brahme, "Optimization of stationary and moving beam radiation therapy techniques," Radiother. Oncol. **12**, 129–140 1988
- Development of MLC around 1990
- S. Webb "Optimizing the planning of intensity-modulated radiotherapy," Phys. Med. Biol. **39**12, 2229–46, 1994
- Convery and Rosenbloom, 1993
- Bortfeld & Boyer, Yu et al, 1994



The Peacock System

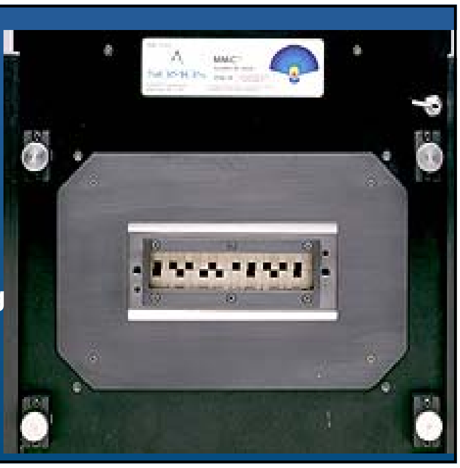
- Carol MP, Targovnik H, Campbell C, Bleier A, Strait J, Rosen B, et al. An automatic 3D treatment planning and implementation system for optimised conformal therapy. In: Minet P, editor. Three dimensional treatment planning. Geneva: WHO, 1992:173–87.
- Grant WH III. Commissioning and quality assurance of an IMRT system. In: Sternick ES (ed): *The Theory and Practice of Intensity Modulated Radiation Therapy*. Madison, WI: Advanced Medical Publishing, 1997, pp 121-126.

Nomos Peacock System



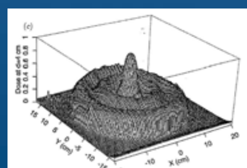
MIMiC

Multileaf
Intensity
Modulat**i**ng
Collimator



IMRT

- A. Brahme, "Optimization of stationary and moving beam radiation therapy techniques," Radiother. Oncol. **12**, 129–140 1988
- Development of MLC around 1990
- S. Webb "Optimizing the planning of intensity-modulated radiotherapy," Phys. Med. Biol. **39**12, 2229–46, 1994
- Convery and Rosenbloom, 1993
- Bortfeld & Boyer, Yu & Wong, 1994


From Yu & Wong 1994

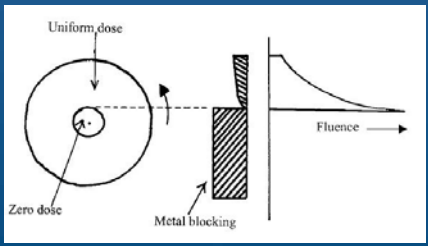
IMRT Delivery

- NOMOS MIMiC delivery technique at Baylor College of Medicine, Houston Texas in March 1994.
- The first dMLC treatments were those at Memorial Sloan Kettering Cancer Institute and Hospital starting in April 1996.
- By 2000 commercial MLC/Linac manufacturers had made available sMLC and dMLC technique linked to inverse planning;
- In 2004 the MIMiC has still delivered the most IMRT but the MLC techniques are catching up;

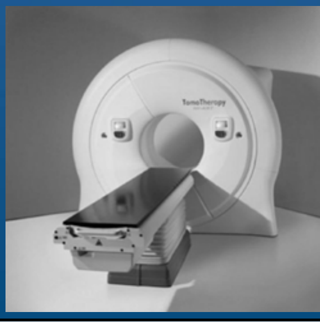
Rotational IMRT

- Brahme A, et al. "Solution of an integral equation encountered in rotation therapy". *Phys Med Biol.* **27** 1221-9, 1982
- Chin LM, et al. "Dose optimization with computer-controlled gantry rotation, collimator motion and dose-rate variation". *Int J Radiat Oncol Biol Phys.* **9** 723-9,1983.
- Mackie T R, et al: Tomotherapy: a new concept for the delivery of dynamic conformal radiotherapy. Med Phys 20(6): 1709-19,1993.
- M. Carol et al. "An automated 3D treatment planning and implementation system for optimised conformal therapy" in *Three-Dimensional Treatment Planning* (Liege: Minet) pp. 173-87,1993
- Yu, CX: Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. Phys. Med. Biol., 40: 1435-49, 1995

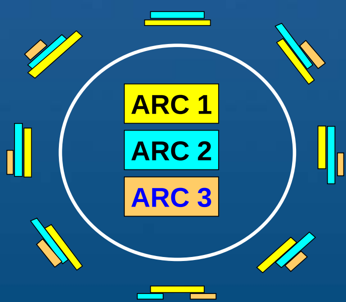
A Brahme, J E Roos and I Lax. Solution of an integral equation encountered in rotation therapy. Phys Med Biol, vol. 27, no. 10, pages 1221–9, 1982.



Commercial Tomotherapy System: 2002

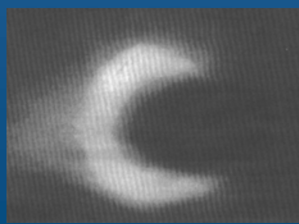


What is IMAT?



IMAT

- Take a NOMOS tomo plan, convert to 36 2D intensity maps
- Sequenc the intensity maps to overlapping apertures
- Convert overlapping apertures into multiple arcs, and
- Deliver by arcing and dynamic MLC motion



Clinical Applications: Pre Single Arc IMAT

- Yu CX, et al 2002 Clinical implementation of intensity-modulated arc therapy. *Int J Radiat Oncol Biol Phys* **53** 453–463.
- Duthoy W, et al. 2003 Whole abdominopelvic radiotherapy (WAPRT) using intensity-modulated arc therapy (IMAT): first clinical experience. *Int J Radiat Oncol Biol Phys.* **57** 1019-1032.
- Duthoy W, et al. 2004 Clinical implementation of intensity-modulated arc therapy (IMAT) for rectal cancer. *Int J Radiat Oncol Biol Phys.* **60** 794-806.
- Wong E, et al. 2005 Intensity-modulated arc therapy for treatment of high-risk endometrial malignancies. *Int J Radiat Oncol Biol Phys.* **61** 830-841.

Publications on IMAT

- **173 publications on IMAT since 1995.**

1. Bratengeier K. 2-Step IMAT and 2-Step IMRT in three dimensions. Med Phys. 2005 32(12):3849-61
2. Cameron C. Sweeping-window arc therapy: an implementation of rotational IMRT with automatic beam-weight calculation. Phys Med Biol. 2005 Sep 21;50(18):4317-36. 2005
3. Duthoy W, De Gersem W, et al. Clinical implementation of intensity-modulated arc therapy (IMAT) for rectal cancer. Int J Radiat Oncol Biol Phys. 2004, 60(3):794-806.
4. Wong E, Chen JZ, Greenland J. Intensity-modulated arc therapy simplified. Int J Radiat Oncol Biol Phys. 2002, 53(1):222-35.
5. Cotrutz C, Kappas C, Webb S. Intensity modulated arc therapy (IMAT) with centrally blocked rotational fields. Phys Med Biol. 2000;45(8):2185-206.

Plan Quality and the Number of Beams

# Angles	Obj. Funct. Value	Std. Dev. in target dose	d_{95}	Mean OAR dose	Integral Dose
3	0.665	0.124	0.747	0.488	2732.5
5	0.318	0.090	0.814	0.215	2563.3
7	0.242	0.064	0.867	0.206	2596.8
9	0.222	0.064	0.855	0.192	2598.3
11	0.202	0.058	0.879	0.186	2570.2
15	0.187	0.053	0.908	0.180	2542.9
21	0.176	0.049	0.912	0.171	2545.1
33	0.151	0.038	0.933	0.155	2543.5

Dave Shepard, et al: *A simple model for examining issues in radiotherapy optimization.* Med Phys, 1999. **26**(7): p. 1212-21.

*"As the speed of delivery and level of integration increases, the superior dose distributions and optimization of numerous beam angles will push IMRT toward **intensity-modulated arc therapy** paradigms."*

— Thomas Rock Mackie: ***Year End Modality Report - Radiation Oncology***. Advance for Imaging and Oncology Administratotrs, 2004. **14**(12): p. 59-62

Works on single arc IMAT

- MacKenzie MA, Robinson DM. 2002 Intensity modulated arc deliveries approximated by a large number of fixed gantry position sliding window dynamic multileaf collimator fields. *Med Phys.* **29** 2359-65.
- Crooks SM, et al. 2003 Aperture modulated arc therapy. *Phys. Med. Biol.* **48** 1033-1044.
- Earl MA, et al, 2003 Inverse planning for intensity-modulated arc therapy using direct aperture optimization *Phys. Med. Biol.* **48**, 1075-1089
- Cameron C. 2005 Sweeping-window arc therapy: an implementation of rotational IMRT with automatic beam-weight calculation. *Phys Med Biol.* **50** 4317-36.
- Ulrich S, et al. 2007 Development of an optimization concept for arc-modulated cone beam therapy. *Phys. Med. Biol.* **52** 4099-4119.
- G. Tang, M. Earl, S. Luan, S. Naqvi and C.X. Yu, "Converting multiple-arc Intensity-modulated Arc Therapy into a single arc for efficient delivery," *Int. J. Rad. Oncol. Biol. Phys* ***69(3,)*** *Sup*, S673 (2007)
- Otto K 2008 Volumetric modulated arc therapy: IMRT in a single gantry arc. *Med Phys.* **35** 310-317.
- Wang C, Luan S, Tang G, Chen DZ, Earl MA, Yu CX, 2008 Arc-Modulated Radiation Therapy (AMRT): A Single-Arc Form of Intensity-Modulated Arc Therapy. *Phys. Med. Biol.* **53** 6291-6303.

Commercial Adoption

- Varian first commercialized Otto's VMAT with RapidArc
- Elekta Developed their single arc solution and call it VMAT
- Philips has recently announce their solution called SmartArc
- Other acronyms: AMAT (aperture modulated arc therapy), AMRT (arc-modulated radiation therapy)

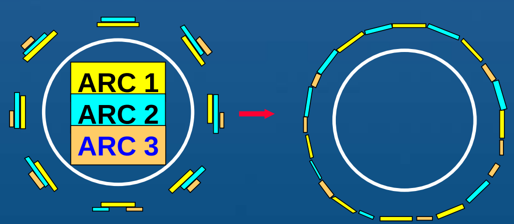
No.1 Principle of IMAT

"The DVHs or subsequently derived biological scores depend on the **total number of strata**, which is defined as the product of the number of beams and the intensity levels within each beam. As the number of beams increases, the number of intensity levels required to obtain optimal dose distribution should be reduced."

Yu, CX: Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy. Phys. Med. Biol., 40: 1435-49, 1995

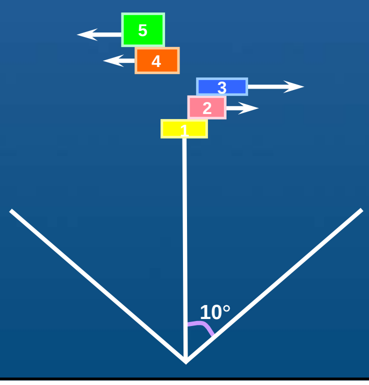
What matters is the total number of shape changes!

Multi-arc to Single arc

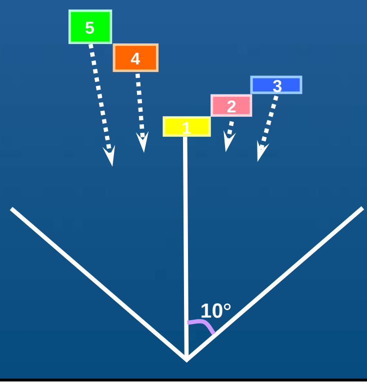


Tang et al, Int. J Rad Onc. Biol Phys, 2007

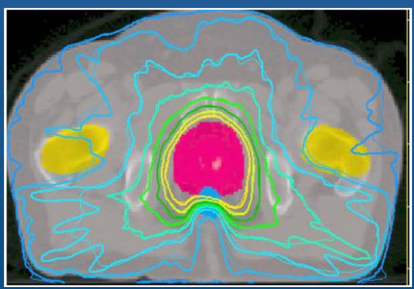
Converting multiple arcs to a single arc …



Converting multiple arcs to a single arc …

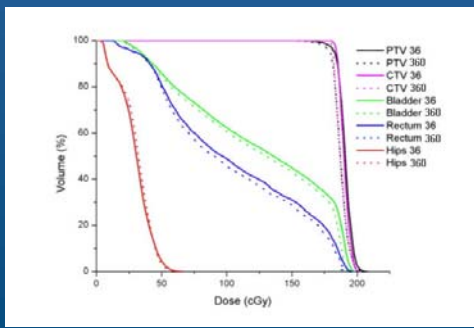


Stacked -> Spaced

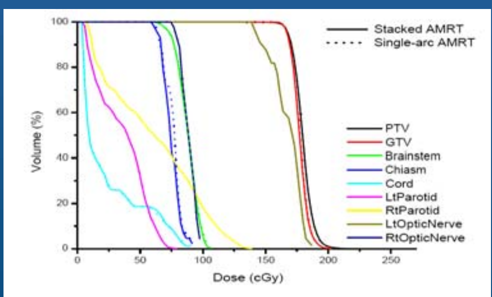


Same total number of strata (shape change), same plan quality

Stack v.s. Spaced DVH



Stacked v.s. Spaced



Same number of apertures, same plan quality

Observation:

Rotational IMRT is insensitive to small angular errors

Understanding Single Arc

- By using large number (100+) of shape variations, intensity modulation is effectively achieved at the target level.
- It is, therefore, capable of achieving IMRT-like plan quality for simple as well as complex cases.

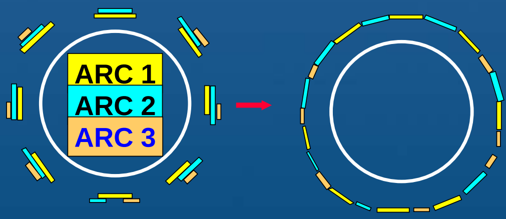
so,

Is it the same as 36 beam IMRT?

In principle: Yes.

In practice: No quite.

This picture ignored deliverability!



Tang et al, Int. J Rad Onc. Biol Phys, 2007

Delivery Requirements

- Neighboring shapes must be geometrically connected.
  - Because deliverability takes priority, shapes are forced to connect in the optimization process, leading to lower plan quality
- Dose rate has to vary in order to maintain (more or less) constant gantry speed.

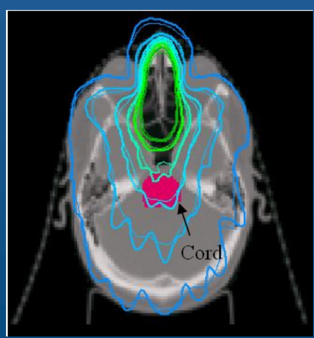
What if I have a fast MLC and fast dose rate variation?

Static Planning for Dynamic Delivery

- All aperture shapes and weights are optimized at fixed angles
- At delivery, the shape is changing continuously, and the dose rate varies to deliver the MUs

Therefore, an optimized shape only appear at an instant, and the MUs for the aperture is delivered through different aperture shapes.

Continuous v.s. static beams

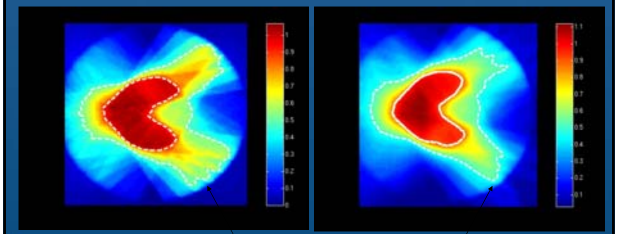


Static beam's Ripple artifact

Planning *vs.* Delivery

Calculated — Planned as static beams

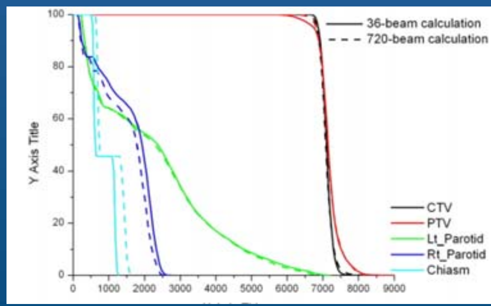
Measured — Delivered as continuous arc



Finger-like artifacts

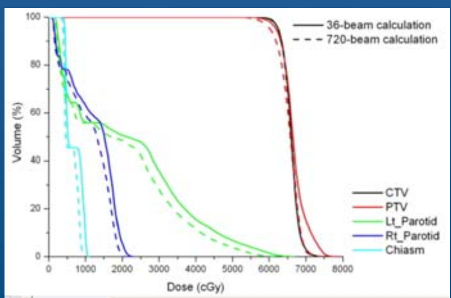
Smooth isodose

Typical Cases – small differences



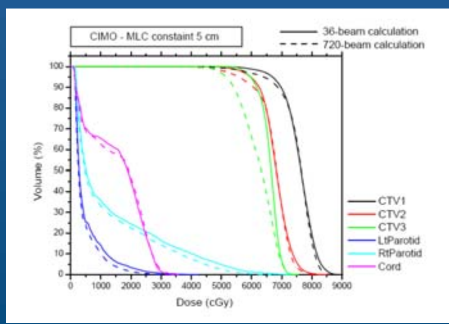
Plan A

Some Cases – noticeable Differences

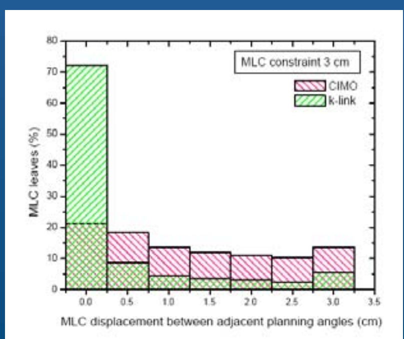


Plan B

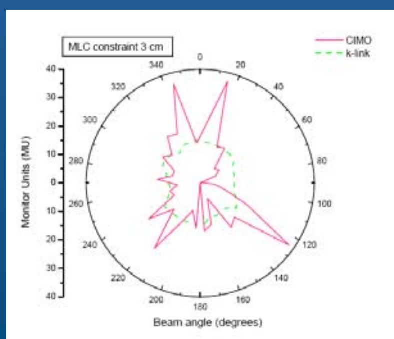
Some Cases – Large Differences



Reason 1: Too much MLC movement



Reason 2: Too Much Dose Rate Variation



Large MLC motion and dose rate variation can cause:

Delivered ≠ Planned

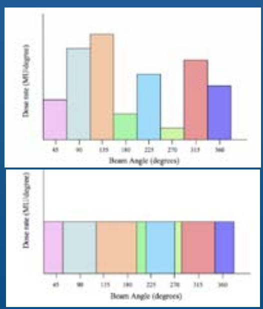
Your machine can do it does not mean you should allow it!

Dose Rate Variation

- Not all machines support variable dose rate
- Large dose rate fluctuation can also lead to delivery errors
- Forcing all apertures to have the same weighting will degrade plan quality!

It would be nice if we could use constant dose rate without limiting the freedom.

Scheme: Similar to AM & FM radio

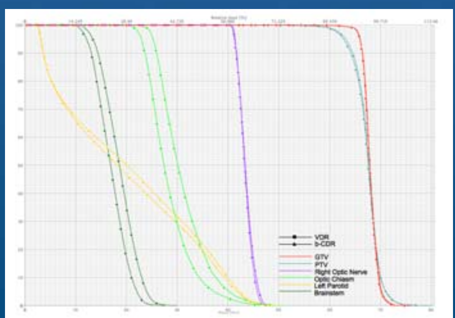


Observation: Rotational IMRT is insensitive to small angular error.

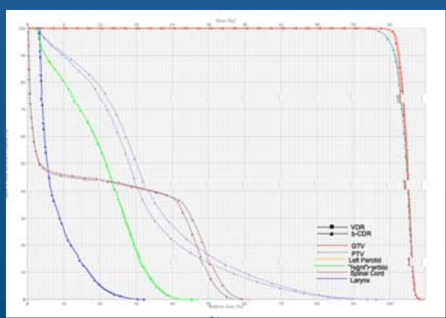
Proof of the idea

- Convert RapidArc Plan (variable dose rate) to Constant Dose Rate delivery
  1. Change even aperture spacing to variable aperture spacing
  2. Apertures with high weights occupy larger angular interval
  3. Limiting angle error to 5 degrees
  4. Re-write the control points for delivery

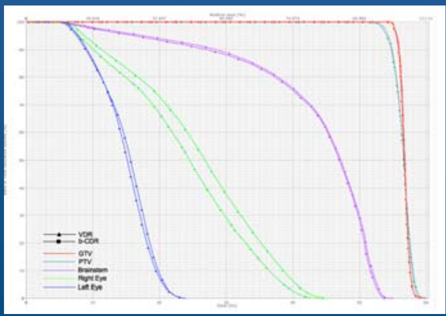
Converting VDR RA to CDR delivery H&N 1



Converting VDR RA to CDR delivery H&N 2

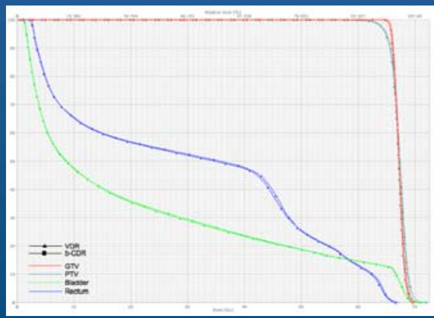


Converting VDR RA to CDR delivery Brain



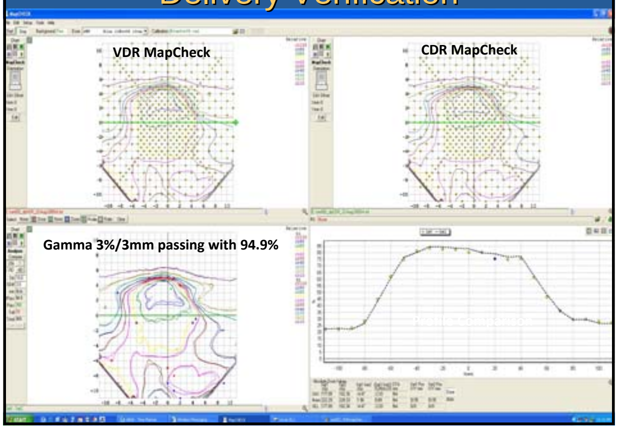
Univ of Maryland

Converting VDR RA to CDR delivery Prostate



Univ of Maryland

Delivery Verification



Delivery Time Comparison

Case	Plan	BOT (min)	MOT (min)	BOT - MOT (min)
HN 1	VDR	1.25	-	1.25
	CDR[6]	2.75	1.32	1.23
HN 2	VDR	1.25	-	1.25
	CDR[3]	1.84	0.64	1.20
HN 3	VDR	1.24	-	1.24
(arc 1)	CDR[5]	2.43	1.23	1.20
(arc 2)	VDR	1.24	-	1.24
	CDR[3]	1.80	0.61	1.19
Brain	VDR	1.25	-	1.25
	CDR[4]	2.38	1.17	1.21
Prostate	VDR	1.68	-	1.68
	CDR[4]	2.35	0.84	1.51

Univ of Maryland

How does IMAT (single or multiple arcs) stack up against other IMRT methods?

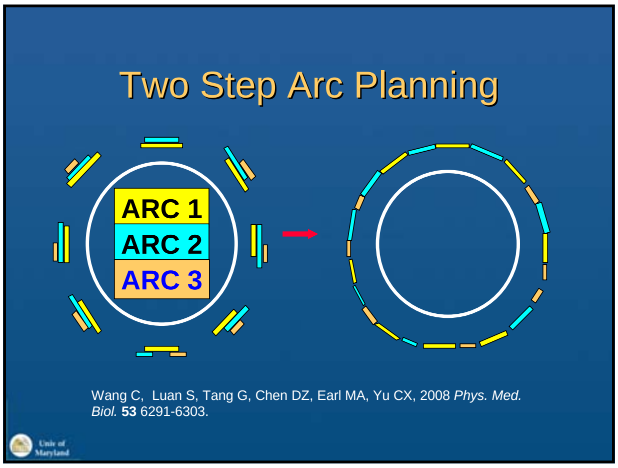
(No trying to be fashionable)

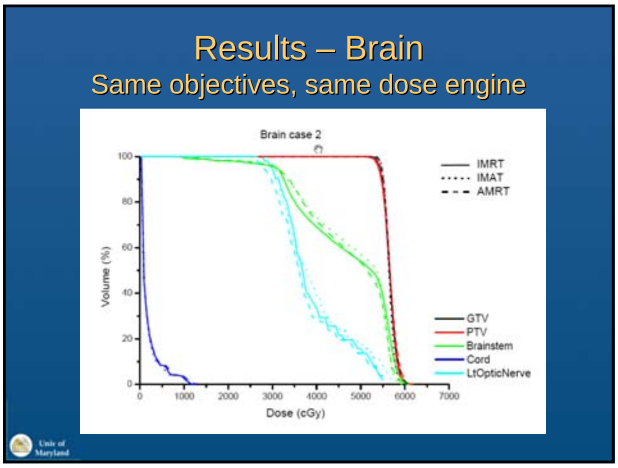
Univ of Maryland

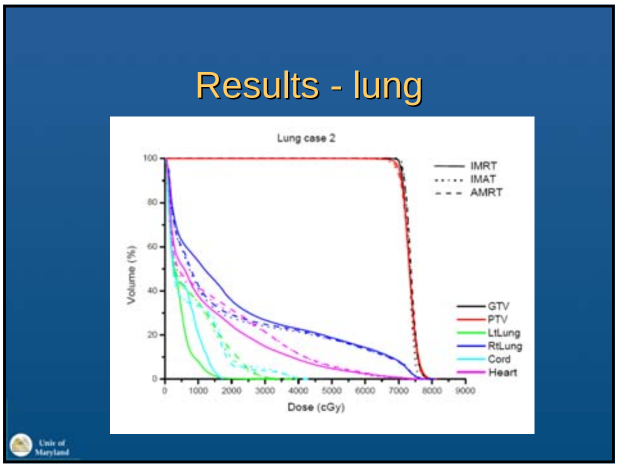
Two Methods of Planning

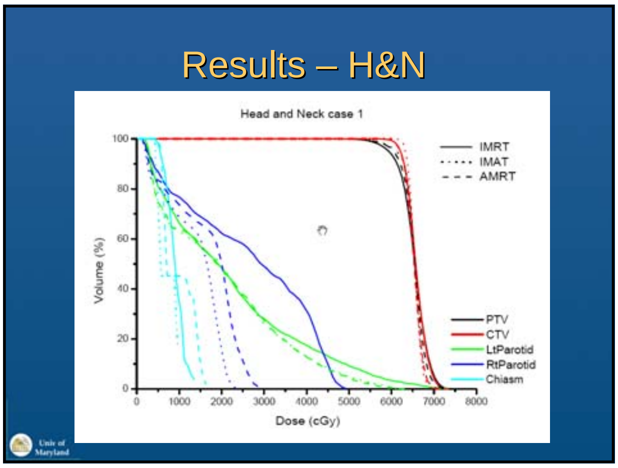
1. Beamlet-based inverse planning
   - Optimize the weights of beamlets to obtain the intensity map, then,
   - Converting the maps to deliverable apertures
2. Aperture-based inverse planning
   - Optimize the shape and weights of apertures

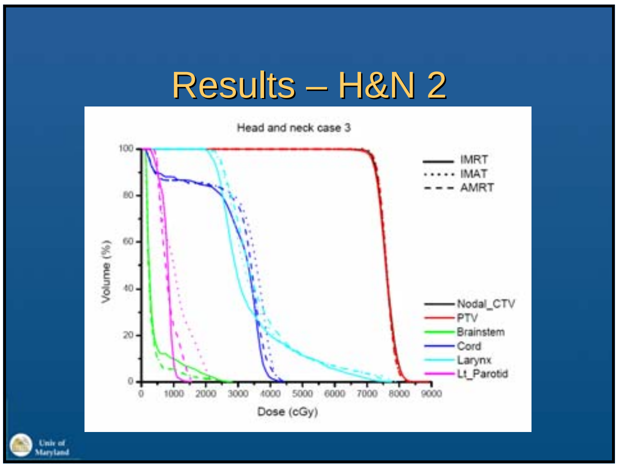
Univ of Maryland

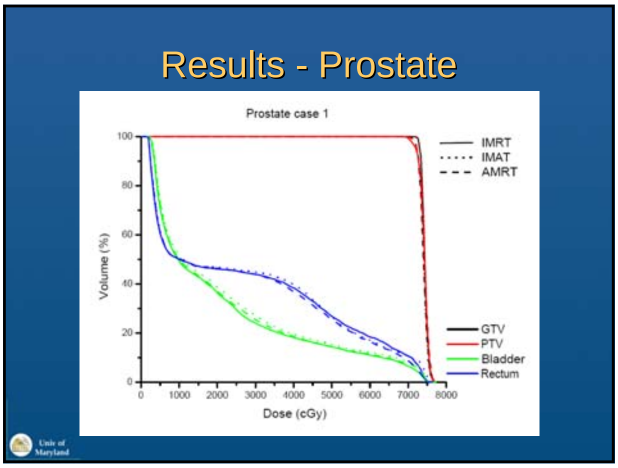

Two Step Arc Planning
ARC 1
ARC 2
ARC 3
Wang C, Luan S, Tang G, Chen DZ, Earl MA, Yu CX, 2008 Phys. Med. Biol. 53 6291-6303.
Univ of Maryland


Results – Brain
Same objectives, same dose engine
Brain case 2
IMRT
IMAT
AMRT
GTV
PTV
Brainstem
Cord
LtOpticNerve
Volume (%)
Dose (cGy)
Univ of Maryland


Results - lung
Lung case 2
IMRT
IMAT
AMRT
GTV
PTV
LtLung
RtLung
Cord
Heart
Volume (%)
Dose (cGy)
Univ of Maryland


Results – H&N
Head and Neck case 1
IMRT
IMAT
AMRT
PTV
CTV
LtParotid
RtParotid
Chiasm
Volume (%)
Dose (cGy)
Univ of Maryland


Results – H&N 2
Head and neck case 3
IMRT
IMAT
AMRT
Nodal_CTV
PTV
Brainstem
Cord
Larynx
Lt_Parotid
Volume (%)
Dose (cGy)
Univ of Maryland


Results - Prostate
Prostate case 1
IMRT
IMAT
AMRT
GTV
PTV
Bladder
Rectum
Volume (%)
Dose (cGy)
Univ of Maryland

Compare IMAT and IMRT for 10 Cases

- Multiple arc IMAT wins every time, but not by much.
- Single arc IMAT performs better than 7-field IMRT in most of the cases

both singe arc and multi-arc IMAT is homegrown

Univ of Maryland

Compare RapidArc™ with Tomotherapy™

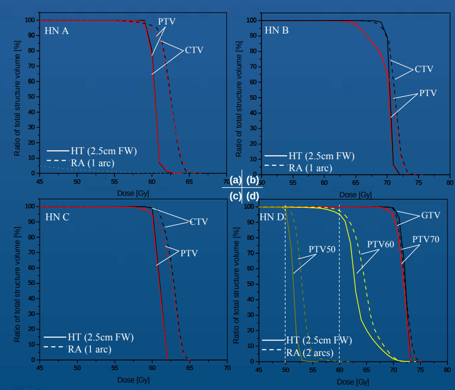
Univ of Maryland

Helical tomotherapy vs. Varian RapidArc: A dosimetric comparison between two institutes

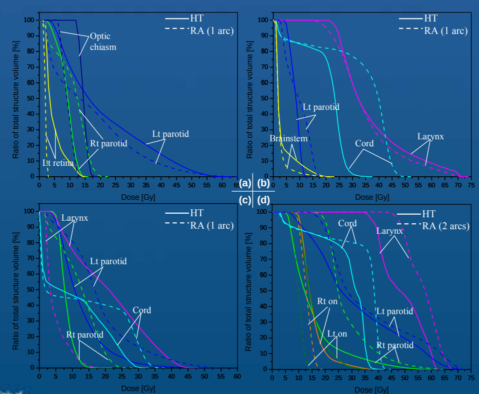
Yi Rong[1], Grace Tang[2], James Welsh[1], Majid Mohiuddin[2], Bhudatt Paliwal[1], Cedric Yu[2]

[1]University of Wisconsin Cancer Center Riverview
[2]University of Maryland School of Medicine

Univ of Maryland

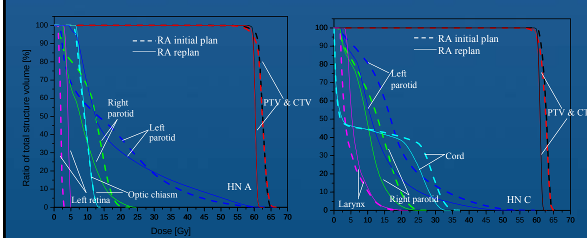


Univ of Maryland

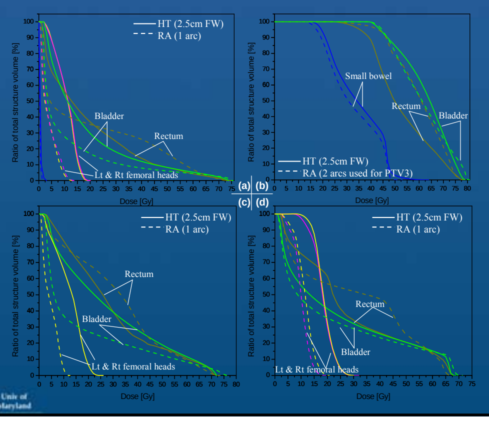


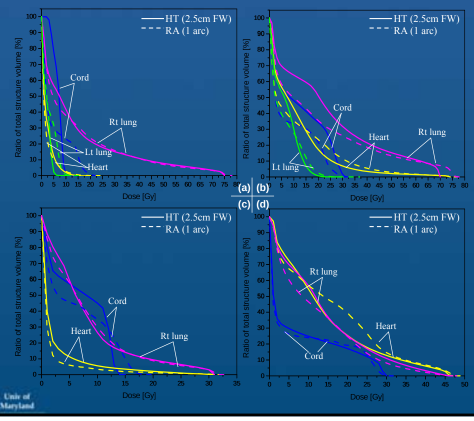
Univ of Maryland

Plan After Unblinding



Univ of Maryland





MUs and Beam-on Time

	RA			HT	
Patient	Arcs	MU	BOT (min)	MU	BOT (min)
Brain A (SEQ)	1	177	0.57	4314	5.10
	2	515	1.23	3581	4.25
Brain B	2	296	1.17	3163	3.77
Brain C (SIB)	2	744	1.91	6820	7.95
Brain D (SIB)	1	441	1.26	3845	4.56
HN A	1	366	1.25	2674	3.22
HN B (SEQ)	1	287	1.23	5027	5.91
	1	418	1.24	4859	5.72
HN C	1	386	1.25	4008	4.74
HN D (SIB)	2	463	2.47	7877	9.16
Prostate A	1	584	1.28	2235	2.72
Prostate B (SEQ)	2	714	2.49	6018	7.03
	1	393	1.25	2725	3.28
	1	494	1.26	2420	2.93
Prostate C	1	744	1.38	5072	5.96
Prostate D	1	940	1.69	4514	5.32
Lung A	1	398	1.25	2851	3.42
Lung B	1	539	1.28	2718	3.27
Lung C	1	470	1.28	3321	3.96
Lung D	1	329	1.27	3579	4.26
Average over 16 cases		**485**	**1.40**	**4081**	**4.83**
Standard deviation		**185**	**0.44**	**1517**	**1.73**

Observations from Comparisons

- For a given case, there are preferred angles and locations to aim the radiation to the target. There are many ways to take advantage of such angular and location preferences.
- Tomotherapy or multi-arc IMAT are subject to less physical constraints. Theoretically, they have more freedom to obtain the optimal solution.
- However, there are many solutions rival such optimal solutions.
- IMAT in either single arc or multi arc form performs at least as well as 7-field IMRT.

Clinical Implementation

- Same as IMRT implementation
- For RapidArc or SmartArc, no new machine commissioning is required if the same planning system is used.
- Start with a simple site, generate an IMRT plan and an IMAT plan to build the team's confidence
- Perform N delivery QAs for each site before going clinical

Dose Calculation

- Calculation time is proportional to the number of beams with current algorithms.
- Vendors are forced to make shortcuts.
- Typical patient specific QA using a homogeneous phantom to compare the calculated and measured doses cannot catch dose calculation errors.
- Must commission with inhomogeneous phantoms!
- Monte-Carlo methods have been shown to out perform with large number of beams.

IMAT QA

COMMISSIONING AND QUALITY ASSURANCE OF RAPIDARC RADIOTHERAPY DELIVERY SYSTEM

C. Clifton Ling, Ph.D.,[*†] Pengpeng Zhang, Ph.D.,[†] Yves Archambault, M.Sc.,[*] Jiri Bocanek, M.Sc.,[*] Grace Tang, M.Phil.,[‡] and Thomas LoSasso, Ph.D.[†]

IMAT involves gantry rotation, dMLC, and variable dose rate. Is it less reliable by default?

- Aperture shape change is enslaved to MUs, proven with dMLC IMRT.
- Both dose rate error and gantry speed error only cause angular errors, to which rotational delivery is known to be insensitive.
- Therefore, if a linac can delivery arc and dynamic IMRT, it can delivery IMAT *reliably.* (passing rates)

IMAT QA

- What is more likely to go wrong?
  - MLC positioning accuracy
- If planning system is not from the linac vendor, be careful about large MLC travel and large dose rate variations
- Phantoms: MapCheck embedded phantoms or similar phantoms (fancy ones require more work and not as intuitive). 3%/3mm pass rate: ~95%
- Couch (stiffening bar) attenuation.

What we learnt?

- The geometric arrangement of the target and ORAs dictates angular and positional preferences.
- Large number of independent apertures are required to take advantage of "the geometry".
- These apertures can be arranged in one arc, multiple arcs, or in a number of fixed fields: "All roads lead to Rome".
- We have only seen improvements in efficiency, not plan quality, over the years.

Conclusion

- IMAT came a long way from Takahashi's dynamic arc in 1965 to today's single arc solutions.
- IMAT has been proven to improve efficiency without sacrificing quality for both simple and complex cases.
- The success lies in the large number of aperture variations (or quanta) and the increased freedom through dose rate or angular spacing variation.
- Plan with static beams may not accurately approximate dynamic delivery, if large MLC travel and dose rate fluctuations are allowed.
- Delivery is not less reliable than dynamic IMRT, but careful commissioning and regular QA is needed.